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14. ABSTRACT

We were funded to participate in the Coupled Boundary Layers/Air-Sea Transfer under low wind (CBLAST-Low) pilot experiment in 2001 and main experiment in 2003 and analyze the data collected from both field campaigns. Our focuses are air-sea interactions under weak winds by analyzing simultaneous measurements of directional waves and atmospheric turbulence. We found that air-sea interactions strongly depend on whether the oceanic wave energy peak is dominated by swell or windsea especially under weak winds. Under weak winds and swell sea, the vertical variation of the momentum transfer is small. As swell dominates oceanic waves and travels in the same direction as wind, low-level jets are commonly observed. As swell dominates oceanic waves and travels in the opposite direction as wind, wind speed tends to increase slightly towards the sea surface and upward momentum flux transfer was observed over the region. As a result, the drag coefficient under weak winds is larger over swell than over wind sea, which explains the previously observed puzzle that the drag coefficient increases with decreasing wind speed under weak winds.

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Final Report

Investigating Characteristics of Air-Sea Interactions in the Wave and Surface Layers[1]

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Abstract

We were funded to participate in the Coupled Boundary Layers/Air-Sea Transfer under low wind (CBLAST-Low) pilot experiment in 2001 and main experiment in 2003 and analyze the data collected from both field campaigns. Our focuses are air-sea interactions under weak winds by analyzing simultaneous measurements of directional waves and atmospheric turbulence. We found that air-sea interactions strongly depend on whether the oceanic wave energy peak is dominated by swell or windsea especially under weak winds. Under weak winds and swell sea, the vertical variation of the momentum transfer is small. As swell dominates oceanic waves and travels in the same direction as wind, low-level jets are commonly observed. As swell dominates oceanic waves and travels in the opposite direction as wind, wind speed tends to increase slightly towards the sea surface and upward momentum flux transfer was observed over the region. As a result, the drag coefficient under weak winds is larger over swell than over wind sea, which explains the previously observed puzzle that the drag coefficient increases with decreasing wind speed under weak winds.

Introduction

There are great interests on whether Monin-Obukhov (M-O) similarity theory is valid over moving oceanic waves. Using the direct numerical simulation (DNS) method, Sullivan et al. (2000) demonstrated that the wind profile does follow M-O similarity law and is not a function of the wave age above 100 z_o, where z_o is the roughness length for momentum. Below that, the wind profile is a function of the wave age defined as c_p/u_*, where c_p is the wave phase speed and u_* is the friction velocity, and does not follow the M-O log-linear profile. In addition, by examing the turbulence energy balance, Hare et al.

[1] Continuation of "Surface Fluxes of Wind-Wave Interactions in Weak Wind Conditions"

(1997), Edson and Fairall (1998), and Wilczak et al. (1999) demonstrated that M-O similarity is valid over moving ocean waves in the surface layer.

Characteristic differences between the surface and wave layers were discussed by Sjoblom and Smedman (2003). Under conditions of strong swell and weak wind, the momentum can be transferred from waves to the air (Smedman et al.1999; Grachev and Fairall 2001). Influences of swell and wind-waves on turbulence eddies are investigated by Smedman et al. (2003). Liu et al. (1996) found that the wind fluctuations were almost in phase with the wave signal for the swell component and had large phase shifts for the wind-wave component. Makin and Mastenbroek (1996) explicitly studied the wave layer and found that turbulent fluxes increased with height and the wave induced fluxes decreased with height, which were observed in the roughness sublayer over land (Nakamura and Mahrt 2001). These results indicate that M-O works over oceans as long as it is above the wave layer, the wave layer is similar to the roughness sublayer over land. Furthermore, as in the roughness sublayer, all the parameters in the wave layer that describe the wave state are important.Theoretically, z_o is the height where the downward extrapolated M-O wind profile in the surface layer vanishes. Since the extrapolated M-O wind profile in the surface layer is not equal to the observed wind in the roughness sublayer, z_o is only an effective roughness parameter, not necessarily the height of any physical roughness elements. Nonetheless, it is related to the physical land surface character (Sun 1999). Therefore, z_o is a dynamic quantity, especially over oceans where the wind at the oceanic surface is not zero, but influenced by the water orbital velocity (Harris 1966).

In addition to the roughness sublayer, Hunt and Carlotti (2001) and Högstrom (1990) found that as large eddies transported by the pressure-wind coherent term are impinged to the ground, there is an eddy sublayer where the turbulence dissipation is found to be larger than the local turbulence generation. As a result, M-O similarity theory does not work close to the ground due to these inactive eddies. Sun (2008) also found that this eddy impinging layer can be deeper than the sublayer affected by roughness elements, in this case waves, where the form drag can be induced by roughness elements.

Our focus of CBLAST-Low (Edson et al. 2007) is to investigate 1) how to measure wave states and atmospheric turbulent fluxes simultaneously to investigate air-sea interactions, and 2) to understand air-sea interactions especially under weak wind conditions by mainly focusing on atmospheric turbulence variations vertically across the wave boundary layer and the marine atmospheric surface layer using the unprecedented dataset of simultaneous measurements of waves and air. Improved understanding of wave effects on marine atmospheric turbulent fluxes under weak wind conditions has significant impacts on modifying the existing bulk aerodynamic formula for numerical models. During this funding period, we mainly focused on the second goal after we successfully retrieved directional wave spectra from laser altimeter measurements as a result of our previous ONR funded project (Sun et al. 2005).

Methods and Approaches

During our previous ONR project, Shoaling Waves Experiment (SHOWEX), we worked with the NOAA LongEZ aircraft on experimenting three laser altimeters on board the aircraft to retrieve directional wave spectra. We combined the SHOWEX and CLBAST-Low Pilot experiment data and developed the new wave-measurement technique where wavelet analysis methods are used. After we lost the LongEZ aircraft in the second phase of the pilot experiment, we worked with the CIRPAS Pelican aircraft group and the WHOI ASIT tower group on analyzing air-sea interactions using the atmospheric turbulent measurements from the Pelican aircraft and atmmospheric and oceanic data at the ASIT tower. As swell phase speeds can be much faster than wind, especially under weak wind, swell can play an active role in air-sea interactions, while wind waves are passive. We focused on effects of swell on turbulence transfer including atmospheric momentum, heat, and moisture fluxes.

To ensure the data quality from the Pelican aircraft, we did tower-aircraft turbulence comparisons based on the days when the CIRPAS Pelican aircraft flew on the level runs along the east-west track near the ASIT tower and the wind direction was good for the tower sonic performance (6 days in total) during the CBLAST-Low main field experiment in 2003 (Sun et al. 2006). We then extend our data analysis to the Pelican aircraft flight days during the main experiment when the ASIT tower data cannot be used because wind direction was from behind the tower structure, therefore the serious flow distortion problem is expected. Those days are July 31, and August 14, 18 and 28, 2003. We also included the LongEZ aircraft data from the pilot experiment in 2001 when the ASIT tower was not there yet. Those aircraft cases allow us to understand air-sea interactions when swell travels in opposite directions of wind, which leads to cases with negative wave age if the wave age is defined by the relative difference between the peak-wave phase speed in the wind direction and the wind speed.

We applied the Ogive method for calculating all turbulent fluxes for the total of 11 flights. The comparison between the aircraft and tower fluxes at four observation heights is done as a function of the atmospheric stability (z/L, where z and L are the observation height and the Ohbukhov length at the lowest observation height on the ASIT tower) and wave age (c_p/ws, where c_p and ws are the peak wave phase speed measured at the tower and wind speed at the top observation level of the ASIT tower, respectively). We chose this definition of the wave to avoid serious self-correlation problems when the wave age is related to turbulent fluxes (Klipp and Mahrt 2004), which is commonly practiced in the community.

Results and Discussions

We investigated influences of swell on momentum, and sensible and latent heat fluxes as functions of the wave age and atmospheric stability using the LongEZ aircraft data collected during the pilot experiment and using the ASIT tower and the Pelican aircraft data collected during the main field experiment under various weather conditions. As we found previously that although the momentum flux derived from the aircraft is flight-direction dependent, which was recently found to be a common problem for all aircraft flux measurements, momentum flux differences between the aircraft and tower measurements was within the uncertainty of the aircraft repeated flights from each mission.

1) Influences of swell on momentum flux

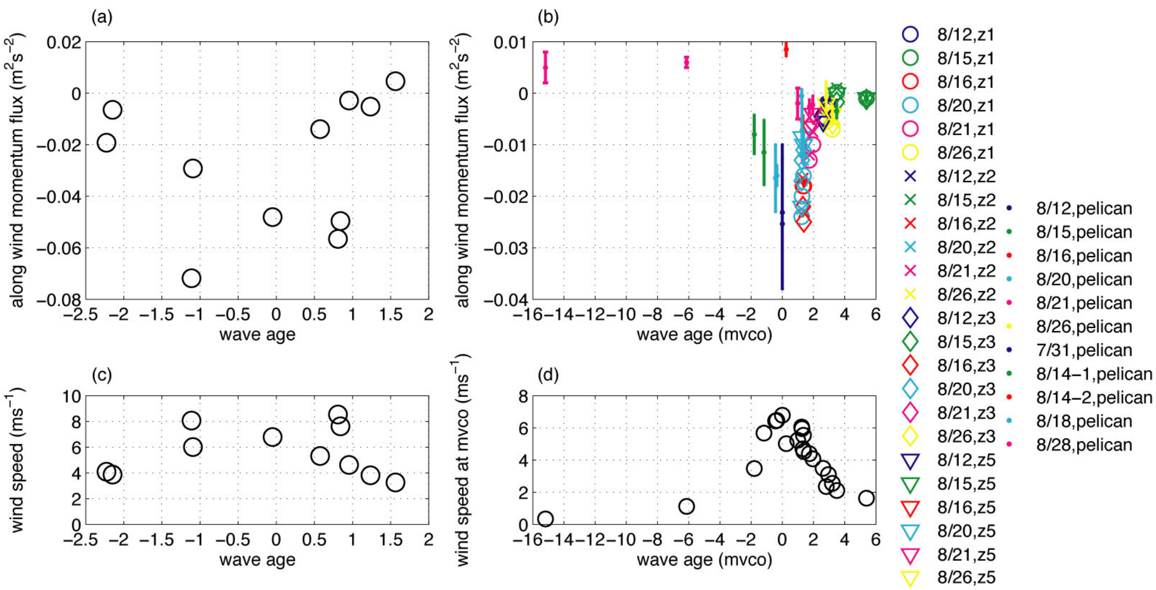

Figure 1: Along-wind momentum fluxes and wind speed as functions of wave age at ~45 m above the sea surface during the Pilot (a and c) and the Main (b and d) experiments. The wave age is calculated as the phase speed of the peak energy wave in the wind direction over the wind speed at the flight level for the pilot experiment, and as the phase speed at the wave energy peak in the wind direction over the wind speed at 10 m at MVCO for the main experiment. The range of the along-wind momentum flux from each Pelican flight mission is marked as the vertical line in (b). The symbols in (b) represent the ASIT measurements at z1,z2,z3, and z5=20 m, where z1,z2 and z3 are 5.86 m, 8.29 m, and 12.03 m before 19 August and 3.59 m, 6.02 m and 9.76 m after.

We found that swell has significant impacts on air-sea momentum fluxes under weak winds (Figure 1). As the wave age increases, the along-wind momentum flux decreases (Figures 1a and 1b), which indicates that when oceanic waves are dominated by swell and wind is weak (Figures 1c and 1d), i.e. when the wave age is large, the wind shear between the atmospheric wind and the oceanic wave is reduced. As a result, the downward momentum transfer from the atmosphere is reduced. As wind blows in the same direction as swell travels, low-level jets are commonly observed due to vertical convergences of momentum (Figure 2). As wind blows in the opposite direction as swell travels on 28 August 2003, we found the increase of wind speed towards the sea surface and upward momentum transfer in the wind direction over most of the sea surface south of Martha’s Vineyard. In general, vertical variations of the momentum flux are small over the swell-dominant-sea since under this situation wind sea is commonly weak.

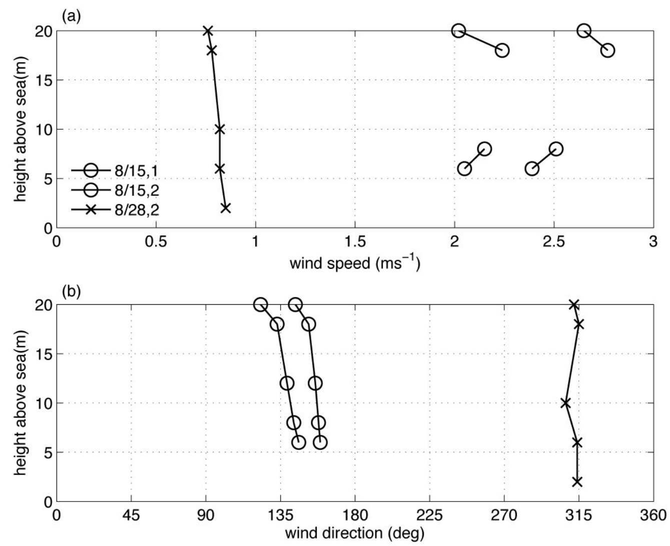

Figure 2. Wind speed (top) and direction (bottom) profiles for the two weak wind days, 15 and 28 August 2003. On 15 August, the wind is in the direction of swell, and on 28 August, the wind is in the opposite direction of swell.

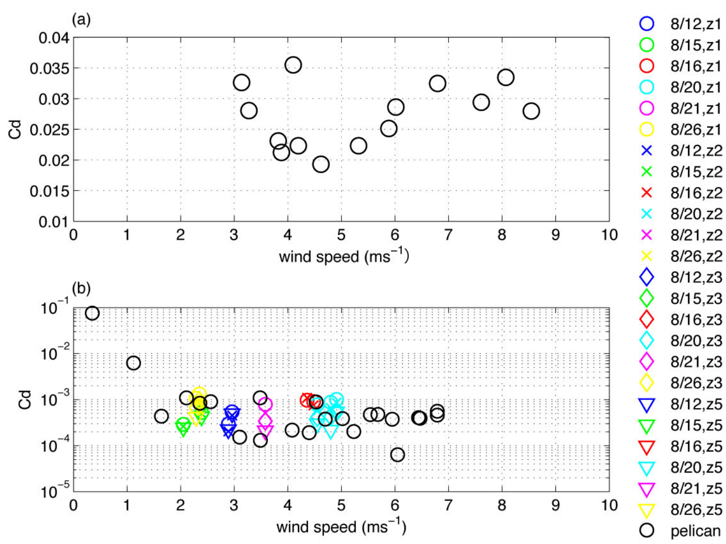

Figure 3. The local drag coefficient (Cd) as a function of wind speed during (a) the pilot and (b) the main experiments. Each symbol in (a) represents Cd from flight-averaged momentum flux and wind speed. Cd from ASIT is calculated using the momentum flux and wind speed at each observation level. Cd from the Pelican is calculated using flight avearged momentum fluxes and wind speeds at 10 m above the sea level at MVCO.

Under weak winds, the drag coefficient is larger over the swell-domiannt-sea than over wind sea. As a result, the drag coefficient is found to increase with decreasing winds under weak winds (Figure 3). The above result is well known but has never been explained satisfactorily. As the influence of swell on the energy exchange across the sea surface, the air-sea interaction observed by the LongEZ and the Pelican aircraft, and the ASIT tower cannot be expained by the traditional M-O similarity theory. Therefore, we cannot follow M-O to convert the drag coefficients in Figure 3 to their neutral conditions, as commonly practiced in the community.

2) Influences of swell on sensible and latent heat fluxes

We found that both heat and moisture fluxes are weak over swell-dominant-sea since the wind is normally weak (Figures 4 and 5). The atmospheric stability is another factor, which influences the magnitude of turbulent fluxes besides the wave effect; however, we do not have enough data to separate the stability and the wave effects. Under windy conditions, wind shear close to sea surface is strong and the influence of swell on turbulence is relatively small.

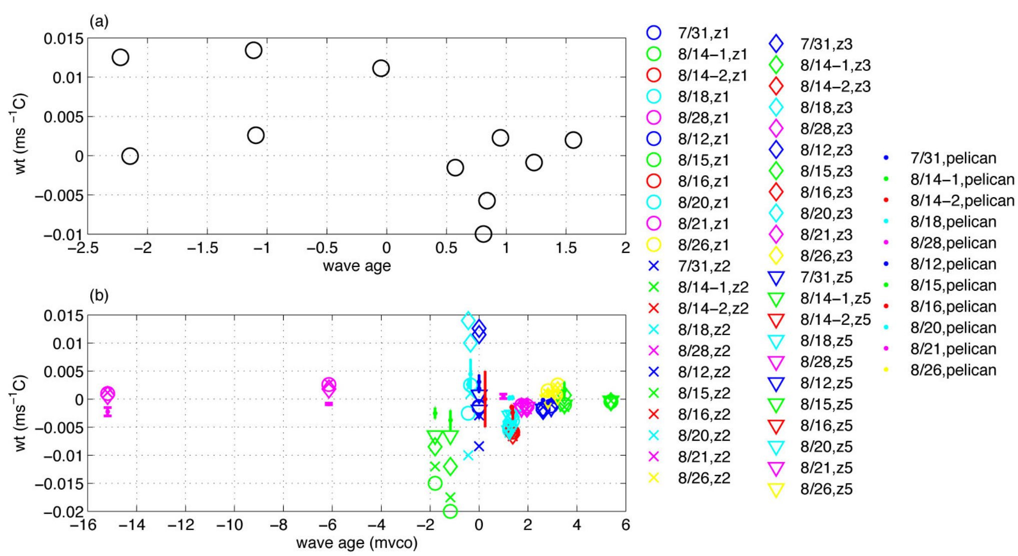

Figure 4: Observed heat fluxes as functions of the wave age from the LongEZ aircraft during the pilot experiment (a) and from both ASIT and the Pelican aircraft during the main experiment (b). Here the symboles are the same as in Figure 1.

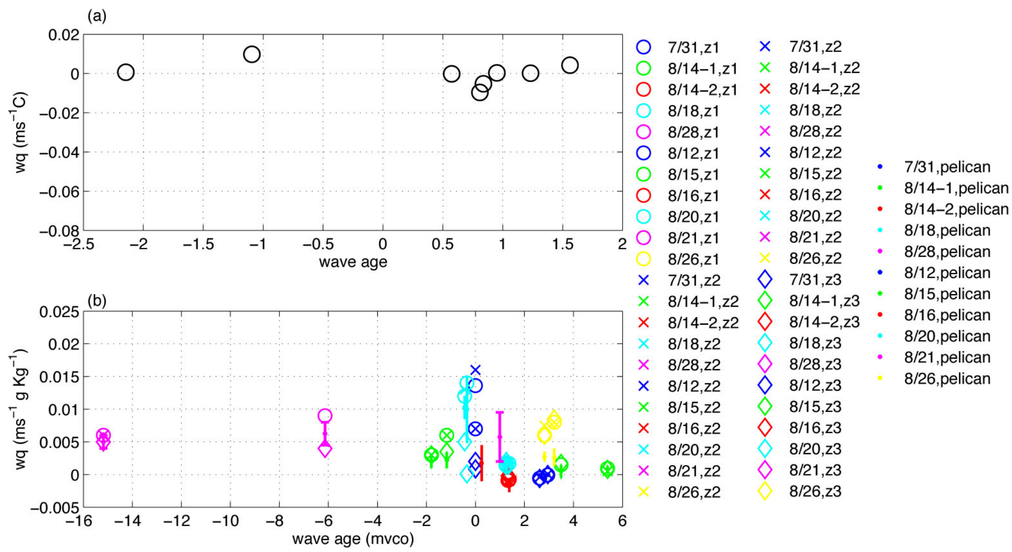

Figure 5: Observed moisture fluxes as functions of the wave age from the LongEZ aircraft during the pilot experiment (a) and from both ASIT and the Pelican aircraft during the main experiment (b).

Conclusions

In the low-wind regime over oceans, swell can travel much faster than wind. Under this situation, the influence of swell on air-sea interactions is evident in all turbulent fluxes across the air-sea interface. If wind is strong, oceanic waves including swell and short waves act as roughness elements over land, which induces drag and slow the air flow. Swell can transport energy into the atmosphere, and reduce shear generated turbulence and the downward atmospheric momentum flux. During the CBLAST-Low Main field campaign, we did observe that the along-wind momentum flux is in the same direction as the wind, which implies that swell can ocassionally provide momentum flux upward instead of draging the atmosphere. However, as the wind direction slashes around under weak wind conditions, the cross-wind momentum can still be negative dragging the atmosphere. Therefore, the momentum flux transfer is never in the direct opposite direction of or in the wind direction, but at an angle from the wind. When swell travels against weak winds, the vector of the momentum flux is more likely in the forward sector of the wind, instead of the backward sector as oceanic waves slow the air flow. Due to interactions between the atmosphere and the mixed slow moving short oceanic waves and fast-moving swell, it is rare that oceanic waves transfer momenutm flux upward to the atmospheric flow.

It is well known that the momentum exchange coefficient increases with wind speed, except for wind is less than about 4 m/s. Although random flux errors and selfcorrelations under weak wind conditions contribute part of the observation that the exchange coefficient for momentum increases with deceasing wind speed under 4 m/s (Mahrt et al. 2003; and Klipp and Mahrt 2004), some real physical processes also contribute to the behavior of the exchange coefficient under weak winds.

Our data analysis results imply that although swell reduces turbulent fluxes at the air sea interface, it also reduces the calculated atmospheric stability (z/L). As a result, turbulence fluxes under swell conditions are actually higher than predicted turbulent fluxes based on the relationship between z/L and turbulent fluxes developed over land. With higher turbulent fluxes and weak wind, the calculated exchange coefficient can be higher for swell cases than for non-swell cases. Therefore, the increase of the exchange coefficient with decreasing wind speed observed in the literature could be partly due to contributions of swell under weak wind conditions. To generalize the above explanation, more data with simultaneous measurements across the air-sea interface are needed. The above results will be published in JGR (Sun et al. 2008).

Recommendations

We found evidences of large drag coefficient under weak winds over swell, which explained the puzzle that led to the CBLAST-Low experiment. Swell can have significant impacts on air-sea momentum transfer, which is more evident under weak winds than under strong winds when windsea dominates. Up to even today, the air-sea turbulence transfer is commonly investigated as a function of wave age or Charnock coefficient, which is defined by the turbulence itself, leading to serious self-correlation problems (Klipp and Mahrt, 2004; Mahrt, 2007). Our results indicate that without careful examinations of oceanic wave frequency distribution and their directional propagation, we would not be able to understand air-sea interactions. Our results also indicate that air-sea interactions are different from air-land interactions because of swell. As a result of the deep wave layer with swell, the traditional Monin-Obukhov similarity theory, which is widely used in numerical models, is not valid in the marine atmospheric boundary layer. Blindly converting drag coefficients to their neutral value, calculating surface roughness based on turbulence and wind measurements at one height, and converting relevant air-sea interaction variables to their 10-m values using M-O similarity theory only lead to scatter relationships and confused results. The existence of swell and its interactions with other oceanic waves under random variations of wind can be the key factor in differences between laboratory and field experiments. With the existence of swell, most of the marine atmospheric boundary layer could be within the wave layer, which is essentially a roughness sublayer. As we know from the air-land interactions, there is no similarity theory available, at least up to now, for any roughness sublayers. Since the boom direction of the ASIT tower is pointed to south where swell comes in, we cannot use tower data to investigate cases when wind blows in the opposite direction of swell.

We need more field data with both high vertical resolutions of atmospheric turbulence measurements and detailed directional wave information available to understand air-sea interactions under various wind and wave conditions. Without any atmospheric turbulence measurements, surface wave measurements cannot be properly interpreted. For the same reason, any air-sea interaction experiment without in-field oceanic measurements would be a waste of money and time.

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